New Insight into the Spatial Distribution of Novae in M31

KAZUHITO HATANO, DAVID BRANCH, ADAM FISHER[1]

Department of Physics and Astronomy, University of Oklahoma, Norman, OK 73019

SUMNER STARRFIELD

Department of Physics and Astronomy, Arizona State University, Tempe, AZ 85287

Received ______________; accepted ______________

[1]Department of Physics, Southwestern Oklahoma State University, Weatherford, OK 73096

ABSTRACT

We use a Monte Carlo technique together with a simple model for the distribution of dust in M31 to investigate the observability and spatial distribution of classical novae in M31. By comparing our model positions of novae to the observed positions, we conclude that most M31 novae come from the disk population, rather than from the bulge population as has been thought. Our results indicate that the M31 bulge–to–disk nova ratio is as low as, or lower than, the M31 bulge–to–disk mass ratio.

Subject headings: dust, extinction — galaxies: individual (M31) — novae, cataclysmic variables

1. Introduction

Opinions about the spatial distribution of classical novae in M31 and in our Galaxy have been undergoing an interesting evolution. The major searches for novae in M31 (Hubble 1929; Arp 1956; Rosino 1964, 1973; Rosino et al. 1989) showed that in a general sense novae are distributed like the light of the galaxy, apart from a possible deficit of novae (a "nova hole") within the central few minutes of arc. By means of a CCD Hα survey, Ciardullo et al. (1987) found novae in the innermost regions and concluded that the nova hole was just due to incompleteness caused by saturation on the photographic plates that had been used in the earlier nova surveys. Ciardullo et al. also concluded that novae in M31 belong overwhelmingly to the bulge population. Capaccioli et al. (1989) reached the same conclusion. At least partly because of the belief that M31 novae are overwhelmingly from its bulge population, it is often assumed that Galactic novae also come mainly from the bulge; for example, Della Valle & Duerbeck (1993) and Della Valle & Livio (1994) assumed that 3/4 of the Galactic novae are from the bulge.

Doubts about the bulge dominance of the M31 nova population arose when Ciardullo et al. (1990) combined the results of their search for novae in NGC 5128 with data on novae in the LMC, SMC, M33, M31, and a few elliptical galaxies in the Virgo cluster. They found the nova rates per unit K–band luminosity to be remarkably similar — apart from a strikingly low rate for the M31 disk. They suggested that since the M31 bulge has been more thoroughly searched for novae than its disk, and since disk novae may be preferentially obscured by dust, it is possible that the nova rate in the M31 disk had been underestimated, and that the nova rate per unit mass of old stellar population may be approximately a constant. Recently, Shafter, Ciardullo, & Pritchet (1996) report that their search for novae in three more galaxies, M51, M101, and M87, has produced preliminary results that are consistent with this proposition.

Another point of view that has developed recently is that young populations are *better* than old populations at producing novae. On the basis of observation, Della Valle et al. (1994) concluded that bulge–dominated galaxies (NGC 5128, M31, M81, and Virgo ellipticals) have a nova rate per unit H–band luminosity that is more than a factor of three lower than that of nearly bulgeless galaxies (LMC and M33). And, on the basis of a binary–star population–synthesis study, Yungelson, Livio, & Tutukov (1997) predict that the nova rate per unit mass of a young population should be much higher than that of an old population. Yungelson et al. find support for that prediction in the nova rates per unit K–band luminosity in the galaxies mentioned above, and they suggest that the apparent dominance of bulge novae in our Galaxy may be due to observational selection effects that favor the discovery of bulge novae over disk novae.

Recently we (Hatano et al. 1997) have used a Monte Carlo technique together with a simple model for the distribution of dust in the Galaxy to investigate the observability and spatial distribution of Galactic classical novae. We concluded that most Galactic novae are indeed produced by the disk, rather than by the bulge. More specifically, we found the distribution of nova apparent magnitudes and positions on the sky to be consistent with the proposition that the Galactic bulge–to–disk nova ratio is equal to that of the overall Galactic bulge–to–disk mass ratio, which is only about 1/7 (van den Kruit 1990). In this Letter we report results of a study which set out to address the question of whether, similarly, the M31 bulge–to–disk nova ratio is consistent with the M31 bulge–to–disk mass ratio, which is about 1/2 (Kent 1989; Hodge 1992).

2. Observations

Since about 1917, more than 300 novae have been discovered in M31. We concentrate on 191 novae that were discovered (or reported) in major surveys carried out at Mount

Wilson (Hubble 1929; Arp 1956) and at Asiago (Rosino 1964, 1973; Rosino et al. 1989), and for which estimates of the peak apparent visual magnitude, V, are available.

Fig. 1 shows the positions on the sky of these novae, on the coordinate system of Capaccioli et al. (1989). At the adopted distance to M31 of 725 kpc ($\mu = 24.3$), six arcminutes corresponds to about 1 kpc. We take the bulge to be spherical, with a radius of 18 arcminutes, or three kpc. Obviously, most of these observed novae are projected within the bulge. The major–to-minor axis ratio of M31 is 4.3, for an inclination of 77 degrees. The ellipse in Fig. 1 corresponds to a circle in the disk, of radius 8.8 kpc (where, as described below, the density of the dust peaks in our model). Note that a great deal of disk is projected within the adopted perimeter of the bulge.

We define "apparent bulge" novae to be those whose sky positions are within the 18–arcminute radius of the bulge, and "apparent disk novae" to be those whose positions are not. As discussed below, some of the apparent bulge novae actually are disk novae. The top panel of Fig. 2 shows the V–distributions for the 176 apparent bulge novae, the 15 apparent disk novae, and the sum of the two. (For comparison, the shape of our model V–distribution, to be discussed below, also is shown in the top panel.)

3. The Model

The Monte Carlo technique that we have developed was inspired by one that was used by Dawson & Johnson (1994) in an interesting study of the observability of historical supernovae in our Galaxy. We (Fisher et al. 1997) constructed an independent Monte Carlo code and used it to extend the work of Dawson and Johnson by considering the observability of hypothetical "ultra–dim" supernovae in the Galaxy, and to consider the observability of supernovae, in the model, from an external point of view. Then we (Hatano

et al. 1997) extended the technique to consider the observability of Galactic classical novae. Here we give a brief description of the model as it is used for this study of novae in M31.

In our previous papers, the Galactic dust was assumed to be distributed according to a simple double exponential law, with a radial scale length of 5 kpc and a vertical scale height of 0.1 kpc. In such a model, the density of the dust peaks right at the center of the galaxy. In M31, however, the density of the dust is known to peak well out in the disk, not far from where most of the current star formation rate is taking place (Hodge 1992). Following Fig. 3 of Xu & Helou (1996), we adopt a simple distribution for the radial dependence of the extinction in M31:

$$A_V = 2.0 - 0.182(8.8 - r), \quad for \;\; r < 8.8 kpc, \tag{1}$$

$$A_V = 2.0 - 0.194(r - 8.8), \quad for \;\; r > 8.8 kpc, \tag{2}$$

where A_V is the total line–of–sight extinction through the inclined disk of M31. This distribution is generally consistent with the various evidence for the radial dependence of extinction discussed by Hodge (1992). The vertical scale height of the dust is taken to be 0.1 kpc, as we used for our Galaxy. In this model, the extinction at $r = 8, z = 0$ kpc is 1.85 mag kpc^{-1}, similar to its value at $r = 8, z = 0$ kpc in our Galactic model, 1.9 mag kpc^{-1}. The major difference between our adopted distributions of dust in the Galaxy and in M31 is the low dust content in the central regions of M31.

Disk and bulge novae in M31 are assigned the same spatial distributions as we used for our Galaxy. Disk novae obey a double exponential distribution, with radial and vertical scale lengths of 5 and 0.35 kpc, and the disk is truncated at $r = 20$ kpc. Bulge novae are taken to be distributed as $(R^3 + a^3)^{-1}$, where R is a radial coordinate, $R^2 = r^2 + z^2$, and

$a = 0.7$ kpc. The bulge is truncated at $R = 3$ kpc, and the disk and bulge components interpenetrate. For Galactic novae, we used a bulge–to–disk nova ratio of 1/7, based on the estimated bulge–to–disk mass ratio of the Galaxy (van der Kruit 1990). For M31, a more reasonable estimate of the bulge–to–disk mass ratio would be 1/2 (Hodge 1992; Kent 1989), so we adopt this as our default value of the M31 bulge–to–disk nova ratio.

The M31 nova luminosity functions also are taken to be the same as we used for novae in our Galaxy. They are gaussian, with dispersions $\sigma(M_V) = 1$, and the mean absolute magnitudes of disk and bulge novae are -8 and -7, respectively.

4. Comparison with Observations

The middle panel of Fig. 2 shows our model V–distributions for true bulge novae, true disk novae (we do know which *model* novae are from the disk and which are from the bulge), and the sum of the two. As can be seen in the top panel of Fig. 2, the total model V–distribution agrees well with the observed V–distribution on its bright side, to $V \simeq 16.5$. However, the model distribution contains a larger proportion of faint novae than the observed distribution. This is due at least in part to observational selection against faint novae (many faint observed novae had to be excluded from our sample because no estimate of peak apparent magnitude was available), but it may also be that our adopted luminosity functions contain too many intrinsically dim novae; in any case this will not affect our main conclusion because it will be based only on the brighter novae. Note that in the mean, the true disk novae are brighter than the true bulge novae. The bottom panel of Fig. 2 is like the middle one, except that now the model novae are divided into *apparent* disk and *apparent* bulge novae, on the basis of whether or not their projected positions are within 18 arminutes of the center of M31. Because of the presence of true disk novae masquerading as apparent bulge novae, the difference between the V–distributions of the apparent disk

and apparent bulge novae is smaller than the difference between the V–distributions for the true disk and true bulge novae. In the middle panel of Fig. 2, almost all of the bright novae are true disk novae, but in the lower panel, many of those true disk novae become apparent bulge novae. And, even though our input model bulge–to–disk nova ratio is only 1/2, the apparent bulge novae outnumber the apparent disk novae. Therefore, according to our model, *a large fraction of the apparent bulge novae in M31 actually are disk novae.*

Some insight into what is going on (at least in the model) can be gained from Fig. 3, which shows a side view of the spatial distribution of model novae having $V < 20$; for clarity, the vertical scale is expanded by a factor of five. First, many true disk novae having $r < 13.9$ kpc are seen as apparent bulge novae. Second, while true bulge novae on the top side of the bulge are practically unextinguished, from our vantage point, true bulge novae on the bottom are significantly extinguished by dust that is well out in the disk, where the extinction is largest. This means that *true bulge novae projected onto the top of the bulge are, in the mean, brighter than those projected onto the bottom.* As can be inferred from looking at Fig. 3, the V–distributions of true disk novae, on top and bottom, show a considerably milder difference.

Fig. 3 suggests a way to estimate the actual M31 bulge–to–disk nova ratio, just by looking at the bottom–to–top ratio (the BTR) of apparent bulge novae — and thus avoiding the issue of the extent to which the bulge has been searched more thoroughly than the disk. Because Fig. 2 shows that our model V–distribution only fits the observed V–distribution on its bright side, we now confine our attention to novae having $V < 17$. The BTR of observed apparent bulge novae having $V < 17$ (see Fig. 1) is 0.83 ± 0.22, where the uncertainty is from $\sqrt(N)$ statistics. The bottom panel of Fig. 4 shows the model distribution of the sky positions of novae having $V < 17$. As expected, true disk novae show a mild asymmetry with respect to the major axis, while true bulge novae are

strongly concentrated to the top. The top panel of Fig. 4 is for an adopted bulge–to–disk ratio of nine, instead of 1/2, *i.e.*, for the case in which M31 novae are overwhelmingly from the bulge. Fig. 5 is like Fig. 4, but showing enlarged views of the bulge. For the model bulge–to–disk ratio of 1/2 (bottom panel), the BTR of apparent bulge novae is 0.57. For the bulge–dominated case (top panel) the BTR ratio of apparent bulge novae is only 0.25, and the disagreement with the sky positions of observed novae having $V < 17$ (Fig. 1) is obvious.

5. Discussion

We have found that the assumption that M31 novae come overwhelmingly from the bulge produces results that are inconsistent with observation. Instead, adopting an M31 disk–to–bulge nova ratio that is like the M31 disk–to–bulge mass ratio produces results that our acceptable. This would be consistent with the proposition that the nova rate per unit K–band luminosity is approximately constant (Ciardullo et al. 1990; Shafter et al. 1996).

If we take our simple model literally we can go further and derive the M31 bulge–to–disk nova ratio that actually reproduces the observed BTR of 0.83 ± 0.22. Fig. 6 shows the dependence of the model BTR on the percentage of true bulge novae, for three different degrees of dustiness — our standard case as described by eqns (1) and (2); twice as dusty; and half as dusty. For our standard dust model, even zero percent bulge novae yields a BTR that is not quite as high as the observed one; within the statistical uncertainty of the observed BTR the upper limit on the percentage of bulge novae is 25 percent, *i.e.*, a bulge–to–disk nova ratio of 1/3. This would be consistent with the proposition that young populations are better at producing novae than old populations (Della Valle et al. 1994; Yungelson et al. 1997). However, Fig. 6 shows that should M31 be only half as dusty as we have assumed (cf. Han 1996), then our upper limit on the percentage of bulge novae would

be 63 percent, *i.e.* a bulge–to–disk nova ratio of 1.7. In view of the statistical uncertainties associated with the observed BTR, and with our simple model, it probably would be premature to draw any conclusion other than that the M31 bulge–to–disk nova ratio is at least as low as the M31 bulge–to–disk mass ratio.

Now, in order to refine our knowledge of the spatial distribution of novae in M31, what is needed is a carefully controlled search for novae that includes parts of the disk that are unambiguously outside the bulge. It is interesting that of eight M31 novae that were discovered in a recent search by Sharov & Alksnis (1996), only three qualify as apparent bulge novae. As we completed this study we learned that another major search for novae in the disk of M31 is planned (A. Shafter, private communication).

We are grateful to Eddie Baron, Darrin Casebeer, Dean Richardson, and Lev Yungelson for discussions, and to Allen Shafter for correspondence. This work has been supported by NSF grants AST 9417102 and 9417242.

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Fig. 1.— Sky positions of 191 novae observed in M31, for which estimates of peak V are available. The M31 major and minor axes are along the X and Y axes, respectively. Novae within the 18–arcminute ($\simeq$ 3 kpc) circle are "apparent bulge novae". The ellipse represents a circle in the inclined disk, of radius 8.8 kpc. Open and filled circles denote novae having $V < 17$ and $V > 17$, respectively.

Fig. 2.— (*top*): the V–distribution of observed novae in M31; the long–dashed line is for apparent disk novae, the short–dashed line is for apparent bulge novae, and the solid line is the sum of the two. The highest curve is our model V–distribution. (*middle*): The model V–distributions for true disk novae (long–dashed line), true bulge novae (short–dashed line), and their sum. (*bottom*): like the middle panel but for apparent disk and bulge novae.

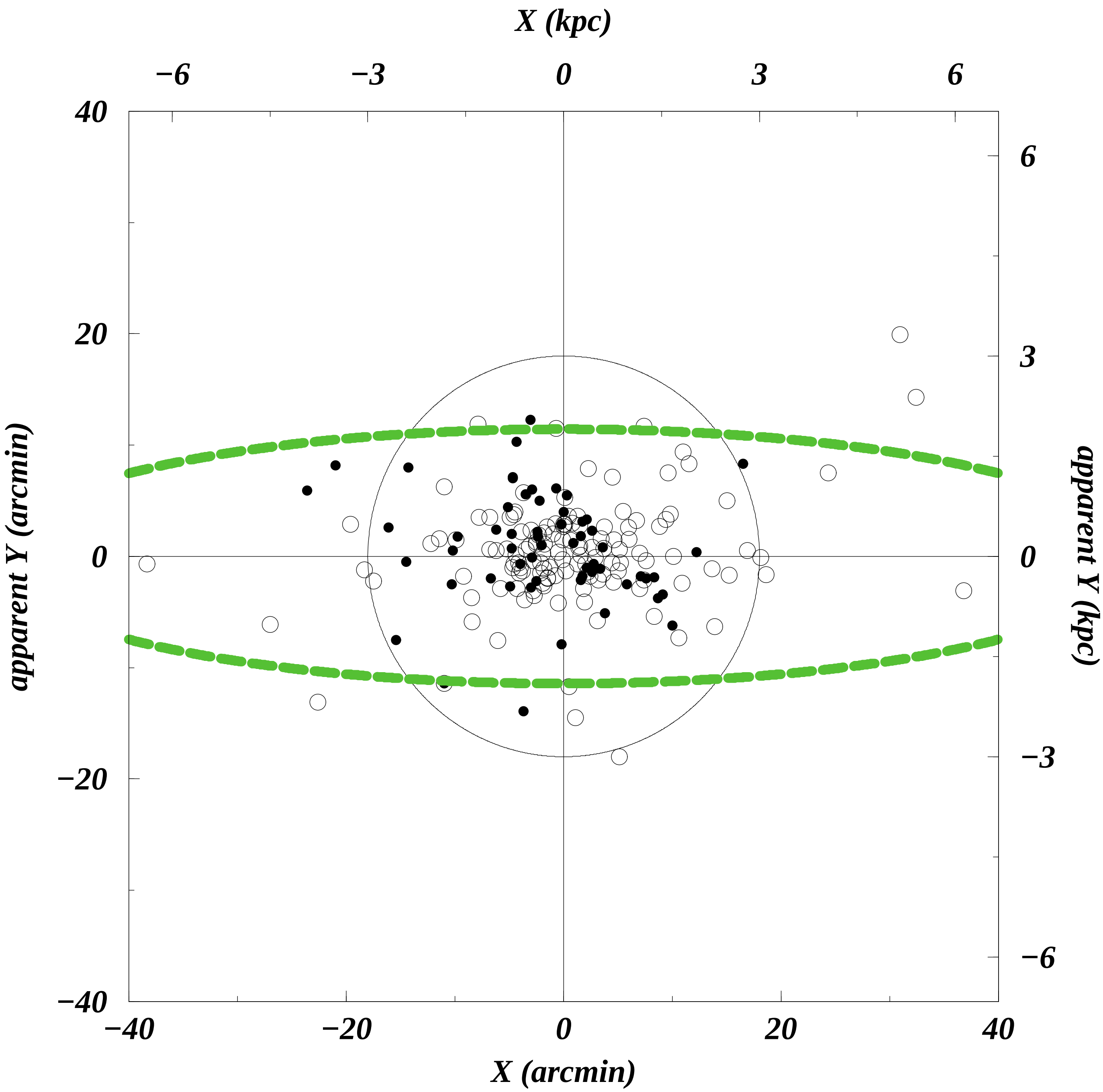
Fig. 3.— A side view of the model spatial distribution of novae in M31. For clarity, the vertical scale is expanded by a factor of five. Our line of sight is from the upper right. Filled and open circles denote true bulge and true disk novae, respectively. Large, medium, and small symbols denote $V < 16, 16 \leq V \leq 18$, and $V \geq 18$, respectively. The widths of the diamond–shaped figures indicate the adopted radial dependence of the dust density. From our vantage point, true bulge novae in the bottom of the bulge tend to be extinguished by dust that is located well out in the disk.

Fig. 4.— *bottom*: the sky positions of model M31 novae having $V < 17$, for our standard bulge–to–disk nova ratio of 1/2. Filled and open symbols denote true bulge and true disk novae, and large and small symbols denote $V < 16$ and $V \geq 16$. *top*: like the bottom panel, but for a bulge–to–disk nova ratio of nine.

Fig. 5.— Like Fig. 4, but with an expanded view of the bulge.

Fig. 6.— The model BTR is plotted against the percentage of bulge novae, for our standard dust model (central slanted line), for twice as dusty (lower slanted line), and half as dusty (upper slanted line). The solid horizontal line represents the observed BTR of 0.83 and the dashed horizontal line represents the statistical lower limit of the observed BTR, 0.61.

Figure 1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−3
0
3
6
40
20
0
−20
−40
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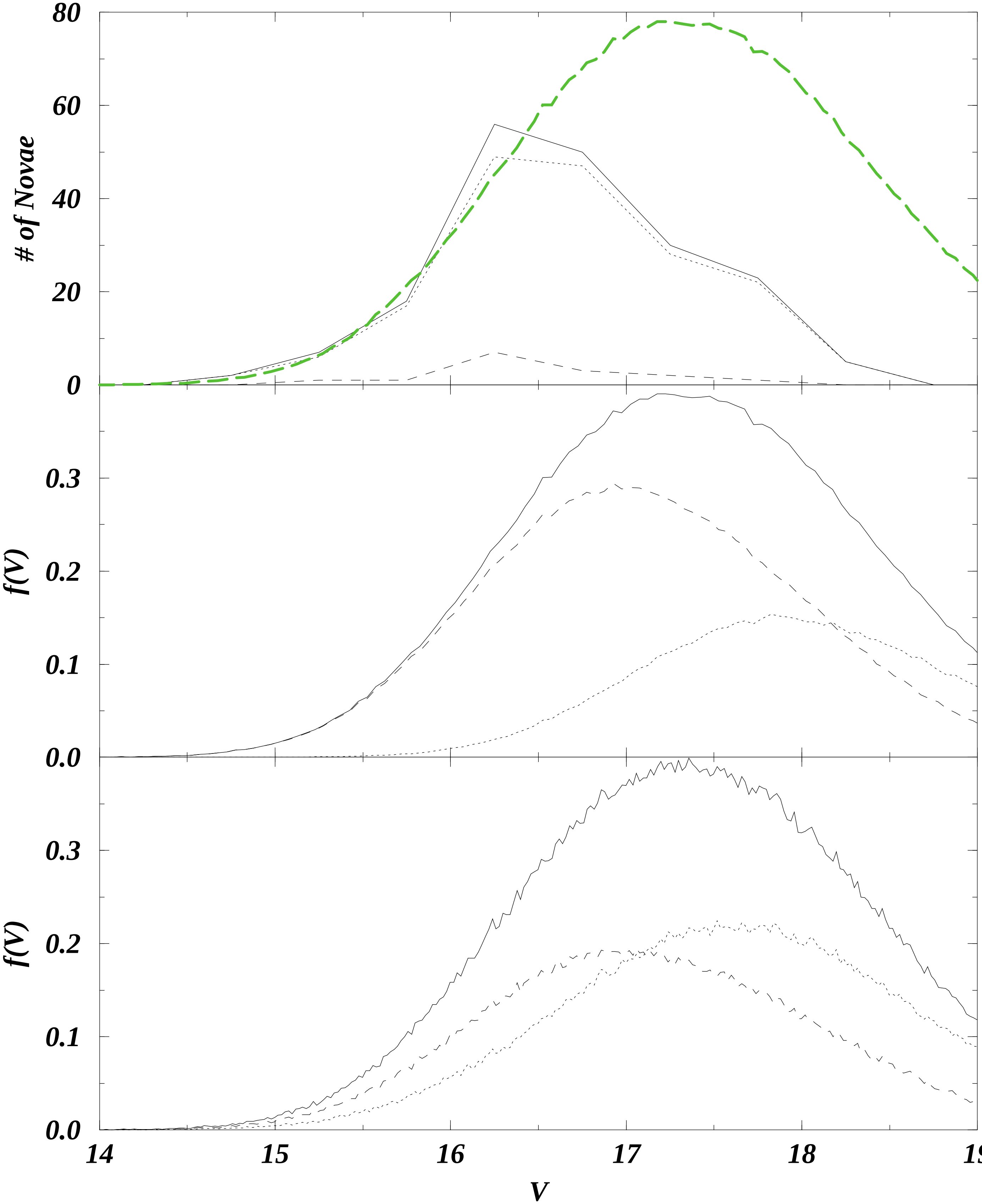
−20
0
20
40
X (arcmin)
apparent Y (arcmin)
apparent Y (kpc)

Figure 2



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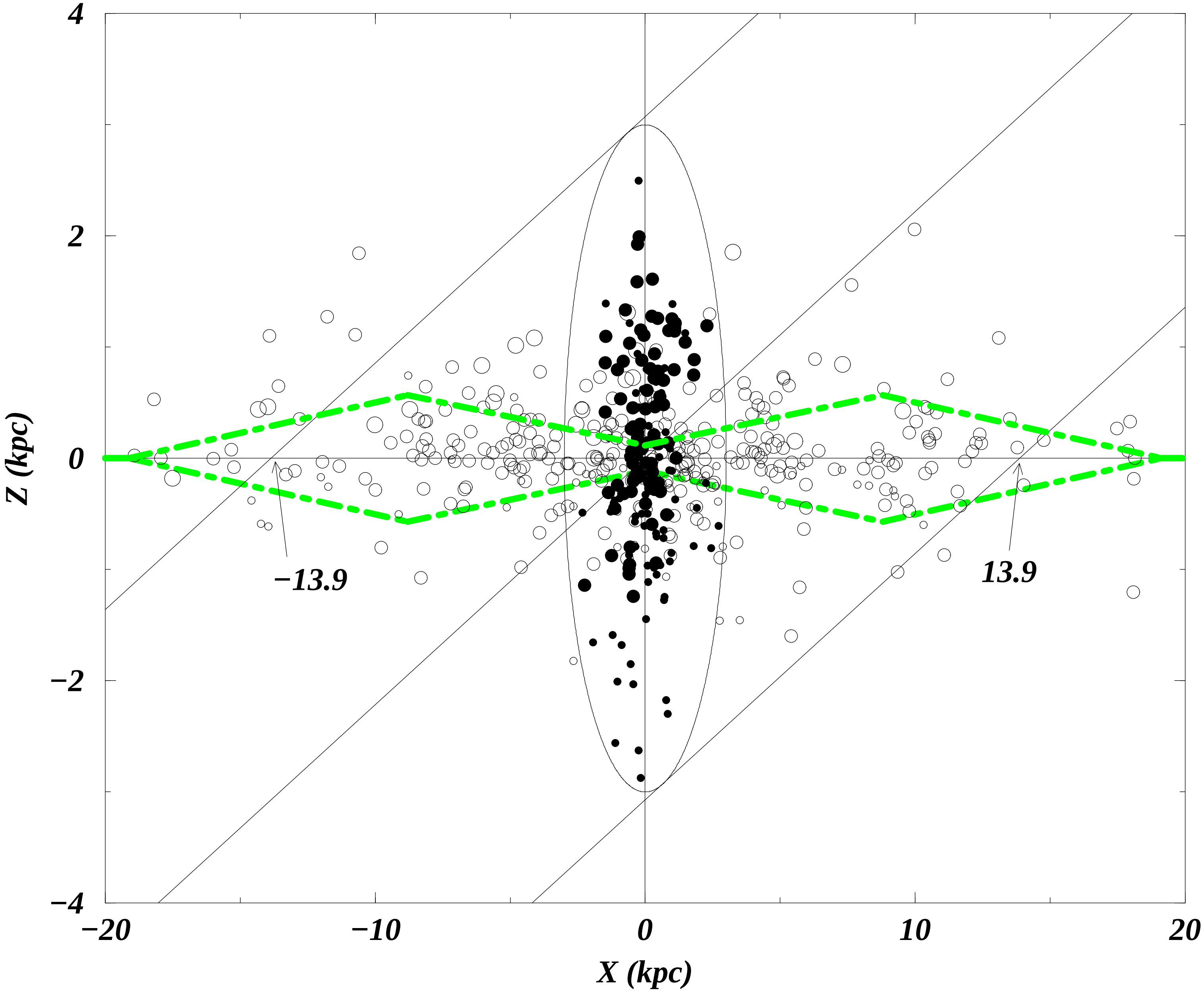

Figure 4

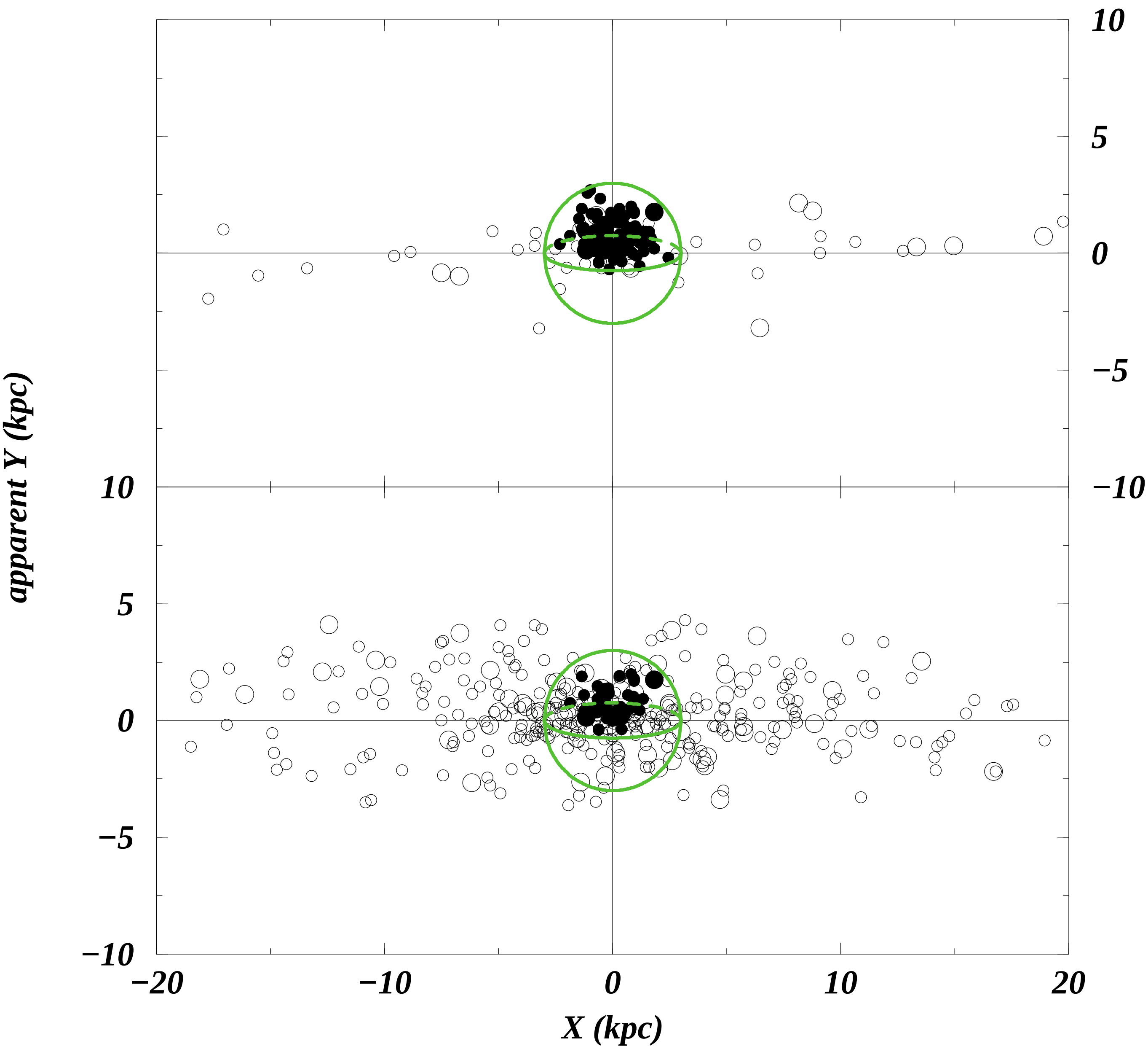

Figure 5

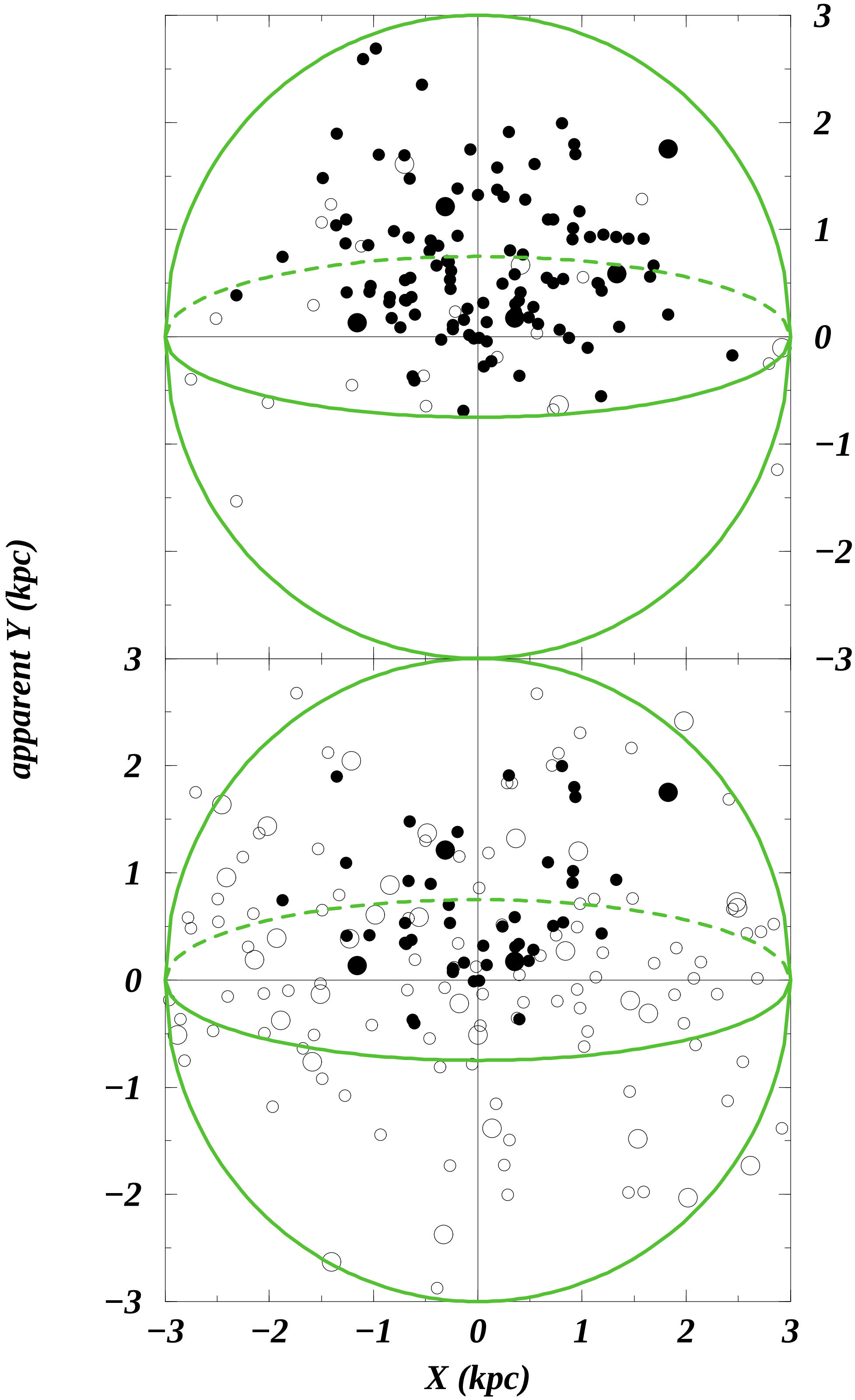

Figure 6